An Innovative Solution to NASA's NEO Impact Threat Mitigation Grand Challenge and Flight Validation Mission Architecture Development*

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Abstract

This paper presents the results of a NASA Innovative Advanced Concept (NIAC) Phase 2 study entitled "An Innovative Solution to NASA's Near-Earth Object (NEO) Impact Threat Mitigation Grand Challenge and Flight Validation Mission Architecture Development." This NIAC Phase 2 study was conducted at the Asteroid Deflection Research Center (ADRC) of Iowa State University in 2012–2014. The study objective was to develop an innovative yet practically implementable mitigation strategy for the most probable impact threat of an asteroid or comet with short warning time ($<$ 5 years). The mitigation strategy described in this paper is intended to optimally reduce the severity and catastrophic damage of the NEO impact event, especially when we don't have sufficient warning times for non-disruptive deflection of a hazardous NEO. This paper provides an executive summary of the NIAC Phase 2 study results. Detailed technical descriptions of the study results are provided in a separate final technical report, which can be downloaded from the ADRC website (www.adrc.iastate.edu).

Keywords—NEO impact threat mitigation, planetary defense, nuclear subsurface explosions, hypervelocity asteroid intercept vehicle (HAIV)

1. Research Motivation and Justification

Despite the lack of a known immediate impact threat from an asteroid or comet, historical scientific evidence suggests that the potential for a major catastrophe created by an asteroid or comet impacting Earth is very real. Humankind must be prepared to deal with such an event that could otherwise cause a regional or global catastrophe. There is now growing national and international interest in developing a global plan to protect the Earth from a catastrophic impact by a hazardous near-Earth object (NEO). This growing interest was recently spurred by the Chelyabinsk meteorite impact event that occurred in Russia on February 15, 2013 and a near miss by asteroid 367943 Duende (2012 DA14), approximately 40 m in size, on the same day.

A variety of NEO deflection/disruption technologies, such as nuclear explosions, kinetic impactors, and slow-pull gravity tractors (GTs), have been investigated by planetary defense researchers during the past two decades [1–10]. To date, however, there is no consensus on how to reliably deflect or disrupt hazardous NEOs in a timely manner. All of the non-nuclear techniques will require mission lead times much longer than 10 years, even for a relatively small NEO. When the time-to-impact with the Earth exceeds a decade, the velocity perturbation needed to alter the orbit of a target asteroid sufficiently to deflect it away from Earth impact is relatively small (approximately 1 to 2 cm/s). Thus, most non-nuclear options as well as a nuclear standoff explosion can be employed for deflection missions when we have sufficiently long warning

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times. It is emphasized that any NEO deflection effort must produce an actual orbital change much larger than predicted orbital perturbation uncertainties from all sources. Likewise, any NEO deflection/disruption approach must be robust against the unknown material properties of a target NEO.

Kinetic impactors and nuclear explosions may be considered as the most mature technologies for asteroid deflection or disruption, as concluded in the 2010 NRC report [10]. Both approaches are impulsive and energy-rich, in that the final momentum change can be considerably more than that present in the original impactor, or in the expanded vaporization layer (from a nuclear standoff explosion). Both methods are expected to eject some debris, and the amount depends on surface material properties. High porosity affects the ability to convert the excess energy into additional momentum. Some asteroids like Itokawa have been determined to have densities (and thus porosities) comparable to terrestrial material with well-characterized shock propagation. Others appear to have very low porosity that may absorb excess energy without the hydrodynamic rebound that can amplify the original impulse.

Because nuclear energy densities are nearly a million times higher than those possible with chemical bonds, a nuclear explosive device is the most mass-efficient means for storing energy with today's technology. Deflection methods with sufficiently high energy density are often preferred over a nuclear disruption approach. One of these deflection methods utilizes a nuclear explosion at a specified standoff distance from the target NEO, to effect a large velocity change by ablating and blowing off a thin layer of the NEO's surface. Nuclear standoff explosions are thus assessed to be much more effective than any other non-nuclear alternatives, especially for larger asteroids. The precise outcome of a NEO deflection attempt using a nuclear standoff explosion is dependent on myriad variables. Shape and composition of the target NEO are critical factors. These critical properties, plus others, would need to be characterized, ideally by a separate mission, prior to a successful nuclear deflection attempt. Other techniques involving the use of surface or subsurface nuclear explosives are assessed to be more efficient than the nuclear standoff explosion, although they may cause an increased risk of fracturing the target asteroid [10].

Nuclear standoff explosions require an optimal standoff distance for imparting maximum velocity change to the target asteroid. Therefore, we have to determine how close the nuclear explosion must be to effectively change the orbital trajectories of asteroids of different types, sizes, and shapes. A simple model that can be used to assess the effectiveness of a nuclear standoff explosion approach is developed in [9]. Geometric principles and basic physics are used in [9] to construct a simple model which can be augmented to account for icy bodies, anisotropic ejecta distributions, and effects unique to the nuclear blast model. Use of this simple model has resulted in an estimation of NEO velocity change of approximately 1 cm/s on the same order as other complex models, and data correlation suggests an optimal standoff distance of about 200 m for an ideal spherical model of a 1-km diameter NEO. The deflection ΔV performance characteristics of nuclear standoff explosions are provided in Fig. 1. However, more rigorous physical modeling and simulation, including hydrodynamic codes and other forms of computer modeling, are necessary to account for changes in material properties under the realistic conditions of the nuclear blast. Possible fracturing of the asteroid and other anticipated outcomes of a nuclear blast must also be assessed in further study. More details of the physical fundamentals of such nuclear standoff explosions can be found in [1, 2, 4].

Due to various uncertainties and constraints in asteroid detection and tracking, the warning time or mission lead time can be very short. An 18-m diameter meteor exploded with the energy of 30 Hiroshima nuclear bombs 30 km above the city of Chelyabinsk, Russia on February 15, 2013, with no warning at all. Asteroid 367943 Duende (2012 DA14), which had a near miss of the Earth on the same day as the Chelyabinsk event, was initially discovered on February 23, 2012. That is, we would have had only one year of warning time if the 40 m DA14 was going to collide with Earth. Another recent example is asteroid 2014 RC, which had a close encounter with Earth on September 7, 2014. This 20-m asteroid was initially discovered on August 31, 2014 by the Catalina Sky Survey near Tucson, Arizona, and independently detected the next night by the Pan-STARRS 1 telescope, located on the summit of Haleakala on Maui, Hawaii. We would have had only one week of warning time if 2014 RC was going to collide with Earth.

If a NEO on an Earth-impacting course is detected with a short warning time (e.g., much less than 5

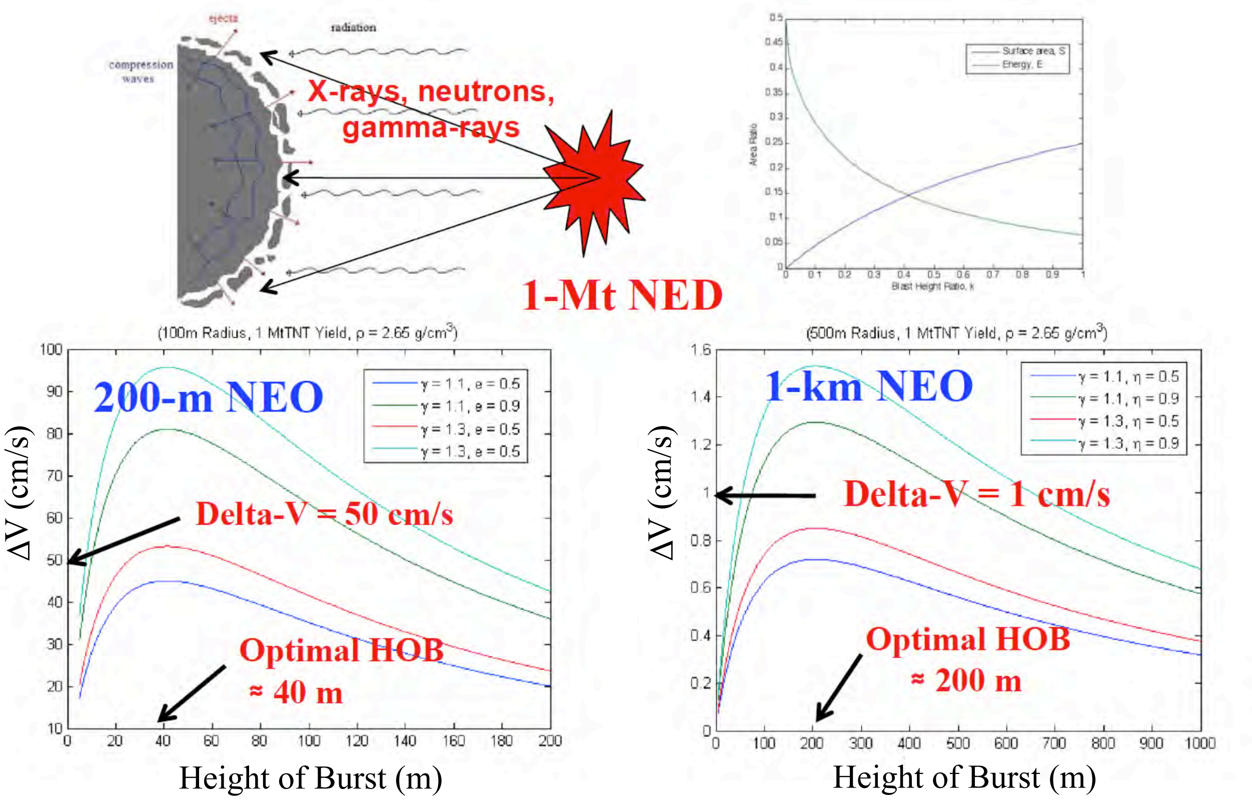

Figure 1: A summary of the ideal deflection ΔV performance characteristics of nuclear standoff explosions [9].

years), the challenge becomes how to mitigate its threat in a timely manner. For a small asteroid impacting in a sufficiently unpopulated region, mitigation may simply involve evacuation [10]. However, for larger asteroids, or asteroids impacting sufficiently developed regions, the threat may be mitigated by either disrupting the asteroid (i.e., destroying or fragmenting with substantial orbital dispersion), or by altering its trajectory such that it will either avoid impacting the predicted impact location, or miss the Earth entirely. When the time to impact with Earth is short, the velocity change required to deflect an NEO becomes extremely large. Thus, for the most probable mission scenarios, in which the warning time is shorter than 5 years, the use of high-energy nuclear explosives in space will become inevitable [10]. A scenario in which a small (e.g., 50 to 150 m) Earth-impacting NEO is discovered with short warning time is considered the most probable scenario because smaller NEOs greatly outnumber larger NEOs, and smaller NEOs are more difficult to detect. Most direct intercept missions with a short warning time will result in arrival closing velocities of 10 to 30 km/s with respect to a target asteroid. A rendezvous mission to a target asteroid that requires such an extremely large arrival ΔV of 10 to 30 km/s is not feasible.

A subsurface nuclear explosion is the most efficient use of nuclear explosives [10, 11]. The nuclear subsurface explosion, even with shallow burial to a depth of 3 to 5 m, can deliver a large amount of energy into the target asteroid, so that there is a likelihood of totally disrupting the target asteroid. Such subsurface nuclear explosions are known to be at least 20 times more effective than a nuclear contact burst (a nuclear explosion very close to the surface) [11]. The momentum/energy transfer created by a shallow subsurface nuclear explosion is at least 100 times larger than that of an optimal standoff nuclear explosion. However, state-of-the-art nuclear subsurface penetrator technology limits the impact velocity to no more than about 300 m/s because higher impact velocities prematurely destroy the fusing mechanisms/electronics of nuclear explosive devices [11]. An increased impact speed limit of 1.5 km/s may be technically feasible as men-

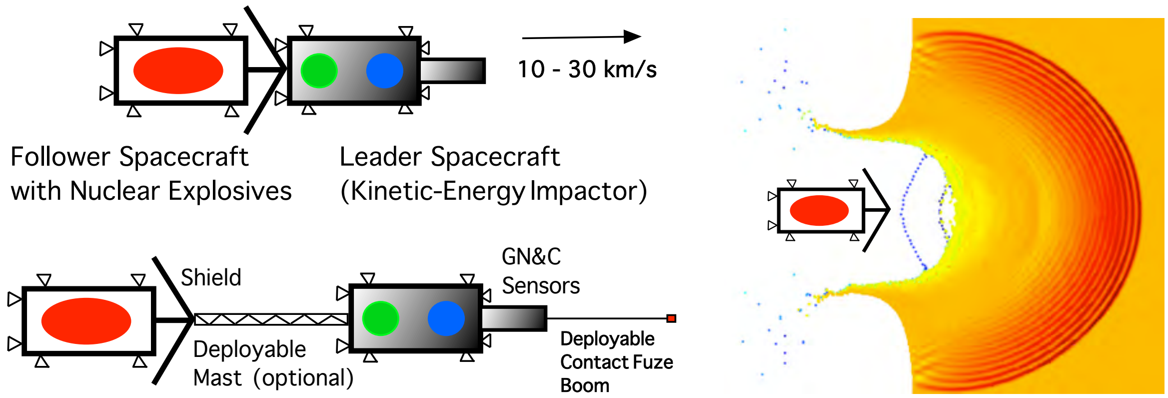

Figure 2: Initial conceptual illustration of a two-body hypervelocity asteroid intercept vehicle (HAIV) system, which was proposed for a NIAC Phase 1 Study in 2011 [12].

tioned in [11] for nuclear Earth-Penetrator Weapons (EPWs). Neither a precision standoff explosion at an optimal height of burst near an irregularly shaped, smaller NEO, with intercept velocities as high as 30 km/s, nor a surface contact burst, is a trivial engineering task.

Despite the uncertainties inherent to the nuclear disruption approach, disruption can become an effective strategy if most fragments disperse at speeds in excess of the escape velocity of an asteroid so that a very small fraction of fragments impacts the Earth. When the warning time is very short, disruption is likely to become the only feasible strategy, especially if all other deflection approaches were to fail, as was concluded in the 2010 NRC report [10]. However, it is again emphasized that non-nuclear techniques should be preferred for non-destructive deflection of hazardous NEOs whenever we have sufficient mission lead times (>10 years).

2. The Major Study Results

2.1 Hypervelocity Asteroid Intercept Vehicle (HAIV) Mission Concept

Our NIAC Phase 2 study was focused on a planetary defense strategy that exploits the innovative concept of blending a kinetic impactor with a subsurface nuclear explosion for mitigating the most probable impact threat of NEOs with a warning time shorter than 5 years. A hypervelocity asteroid intercept vehicle (HAIV) concept has been developed through NIAC Phase 1 & 2 Studies [12–15]. The HAIV is a two-body space vehicle consisting of a leading kinetic impactor and a trailing body carrying nuclear explosives, as illustrated in Figs. 2 through 4. Its flight validation mission architecture has also been designed, and we have identified various key enabling technologies required for the HAIV mission of optimally intercepting and disrupting a target asteroid [12–15].

Most direct intercept missions with a short mission lead time will result in arrival closing velocities of 10 to 30 km/s (relative to a target asteroid). A rendezvous mission to a target asteroid, requiring such an extremely large arrival ΔV of 10 to 30 km/s, is not feasible. A nuclear subsurface explosion, even with shallow burial to a depth of 3 to 5 m, can deliver a large amount of energy into the target asteroid, so that there is a likelihood of totally disrupting the target asteroid. Such subsurface nuclear explosions are known to be at least 20 times more effective than a nuclear contact burst [11]. However, state-of-the-art nuclear subsurface penetrator technology limits the impact velocity to less than about 300 m/s because higher impact velocities prematurely destroy the fusing mechanisms/electronics of nuclear explosive devices [11]. An increased impact speed limit of 1.5 km/s may be technically feasible as mentioned in [11] for nuclear Earth-Penetrator Weapons (EPWs).

In order to overcome such practical constraints on the penetrated subsurface nuclear explosion, the

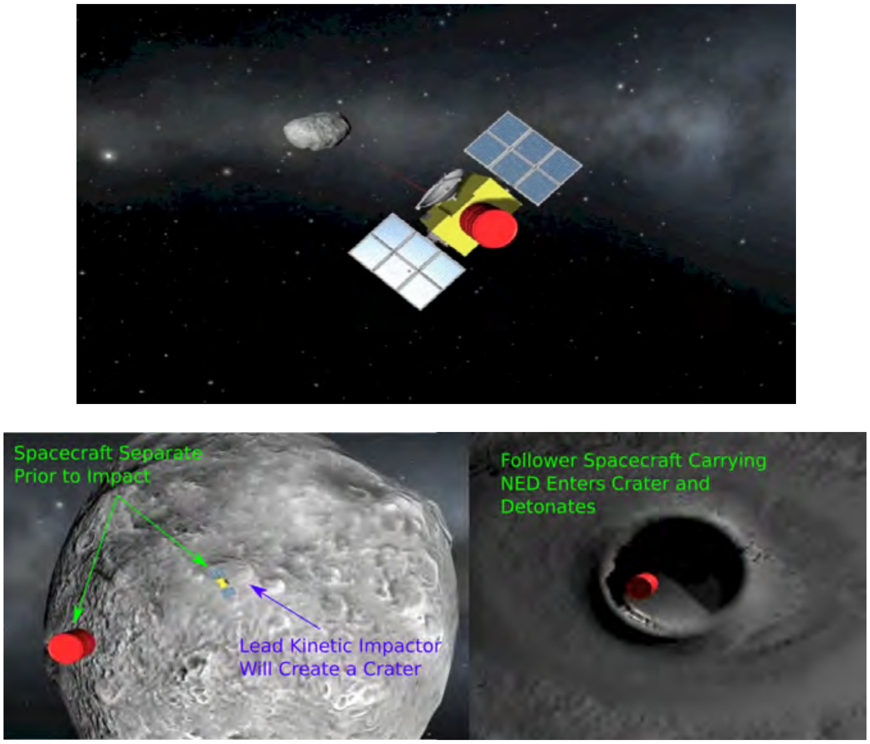

Figure 3: A notional depiction of the HAIV mission concept further investigated for a NIAC Phase 2 Study in 2012–2014.

HAIV system concept has been developed, which will enable a last-minute, nuclear disruption mission with intercept velocities as high as 30 km/s. The proposed HAIV system is a two-body space vehicle consisting of a fore body (leader) and an aft body (follower), as illustrated in Figs. 2 through 4. The leader spacecraft creates a kinetic-impact crater for the follower spacecraft carrying nuclear explosive devices (NEDs) to make a more effective explosion below the surface of a target asteroid body. Surface contact burst or standoff explosion missions will not require such a two-body vehicle configuration. However, for a precision standoff explosion at an optimal height of burst, accurate timing of the nuclear explosive detonation will be required during the terminal guidance phase of hypervelocity intercept missions.

A reference HAIV mission architecture and its terminal guidance phase are illustrated in Fig. 5. For a small (50 to 150 m) target asteroid, the terminal guidance phase may begin 2 hrs prior to the final intercept collision. The nuclear fuzing system may be activated, arming the NED payload, much earlier in the terminal phase operations timeline. Instruments located on the leader spacecraft detect the target NEO, and a terminal guidance subsystem on-board the HAIV becomes active. Measurements continue through optical/IR cameras located on the leader spacecraft and an intercept impact location is identified on the target asteroid body. The high-resolution optical/IR cameras provide successive images of the NEO to the terminal guidance system for a few trajectory correction maneuvers. The leader spacecraft and the follower spacecraft must separate before the leader (leading kinetic impactor) collides with the target NEO.

A variety of existing launch vehicles, such as Delta II class, Atlas V, Delta IV, and Delta IV Heavy, can be used for the HAIV mission carrying a variety of NED payloads ranging from 300-kg (with approximately 300-kt yield) to 1,500-kg (with approximately 2-Mt yield). Conceptual design of an interplanetary ballistic missile (IPBM) system architecture for launching the HAIV system can be found in [16].

Because the hypervelocity kinetic impact and nuclear subsurface explosion simulations rely heavily on energy transmission through shocks, the simulation research work conducted for the HAIV mission concept study [17–19] used Adaptive Smoothed Particle Hydrodynamics (ASPH) to mitigate some of the

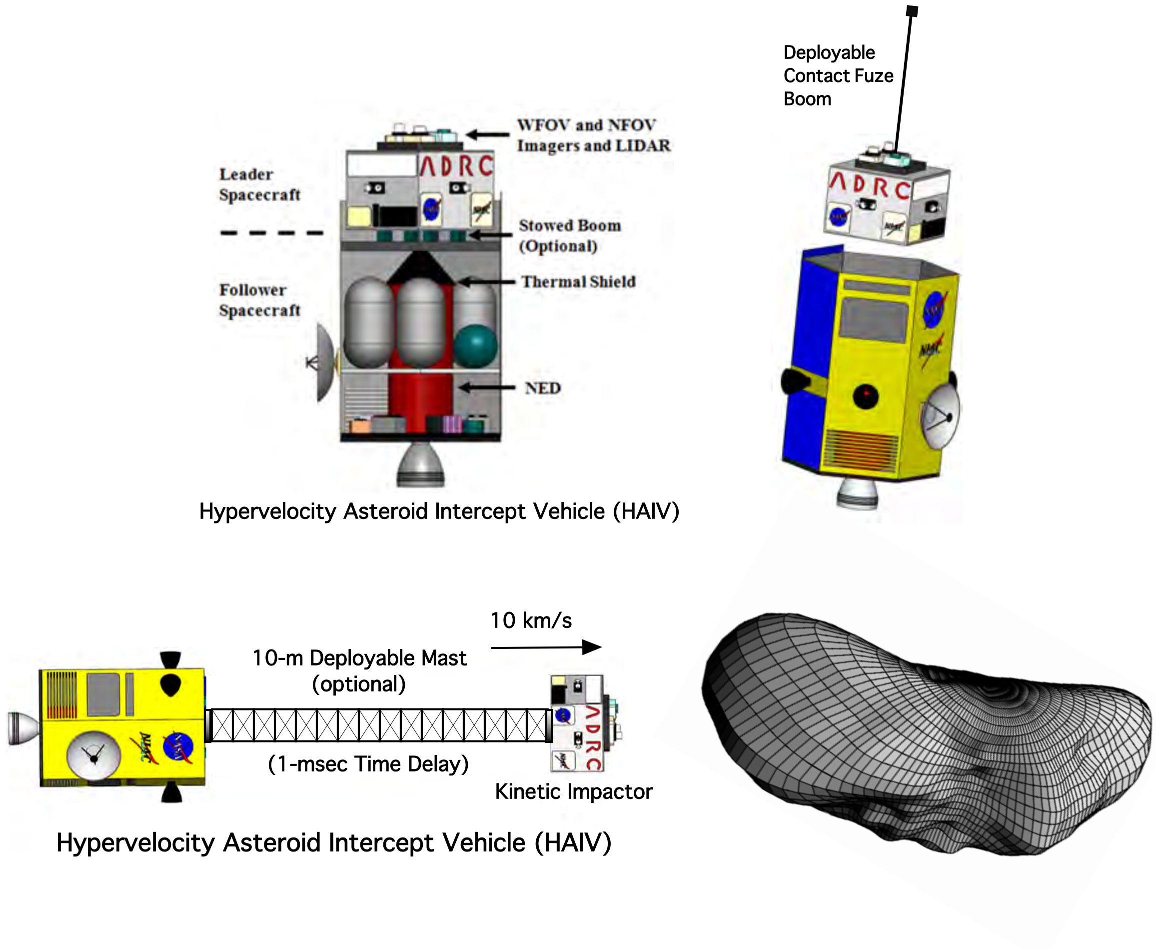

Figure 4: HAIV configuration options [13].

computational and fidelity issues that arise in more complex, high-fidelity hydrocode simulations. The propagation of the nuclear explosive shock can be seen for an illustrative benchmark test case shown in Fig. 6. The shock propagation process dissipates some energy due to interactions with the rebounding shock front. In the center area of deeper regolith, the seeding process naturally results in a much more porous material, absorbing energy from the shock. Upon reaching the second core at the far side, some large chunks escape the disruption process in some cases (even with lower material strengths). An improved ASPH code, implemented on a modern low-cost GPU (Graphics Processing Unit) desktop computer, has been developed for the HAIV mission study [17–19] using the research results of Owen et al. [20]. However, a more computationally efficient, modern GPU-based hydrodynamics code needs to be further developed by incorporating more accurate physical models of a nuclear subsurface explosion [21, 22].

The orbital dispersion problem of a fragmented asteroid in an elliptic orbit, for assessing the effectiveness of an asteroid disruption mission, is illustrated in Fig. 7 [23]. Various approaches have been employed in [23] to be computationally efficient and accurate for several examples with a large number of fragments (e.g., 500,000). An N-body orbit simulation code was also used for orbital dispersion simulation and analysis in [23, 24]. To assess the degree of mitigation, the code includes gravitational focusing effect of the Earth on those fragments that pass near the Earth, and provides a census of those that hit the Earth (i.e., those with a minimum distance to Earth that is <1 Earth radius).

A summary of the effectiveness of nuclear subsurface explosions is presented in Fig. 8 [23,24]. The mass that impacts the Earth is converted to energy in units of Mt using an Earth approach hyperbolic excess speed, V_∞. of 9.98 km/s. From Fig. 8, we notice that a 1-Mt nuclear disruption mission for a 1-km NEO requires

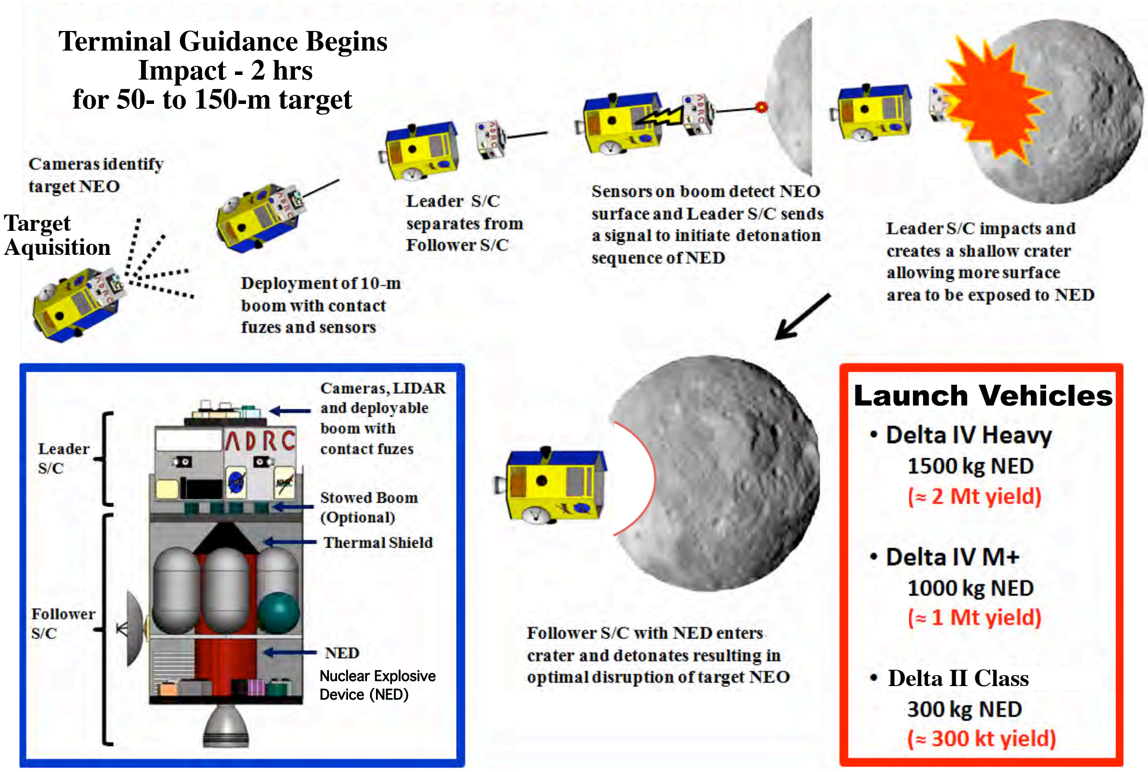

Figure 5: A reference HAIV flight system and its terminal guidance operational concept [13].

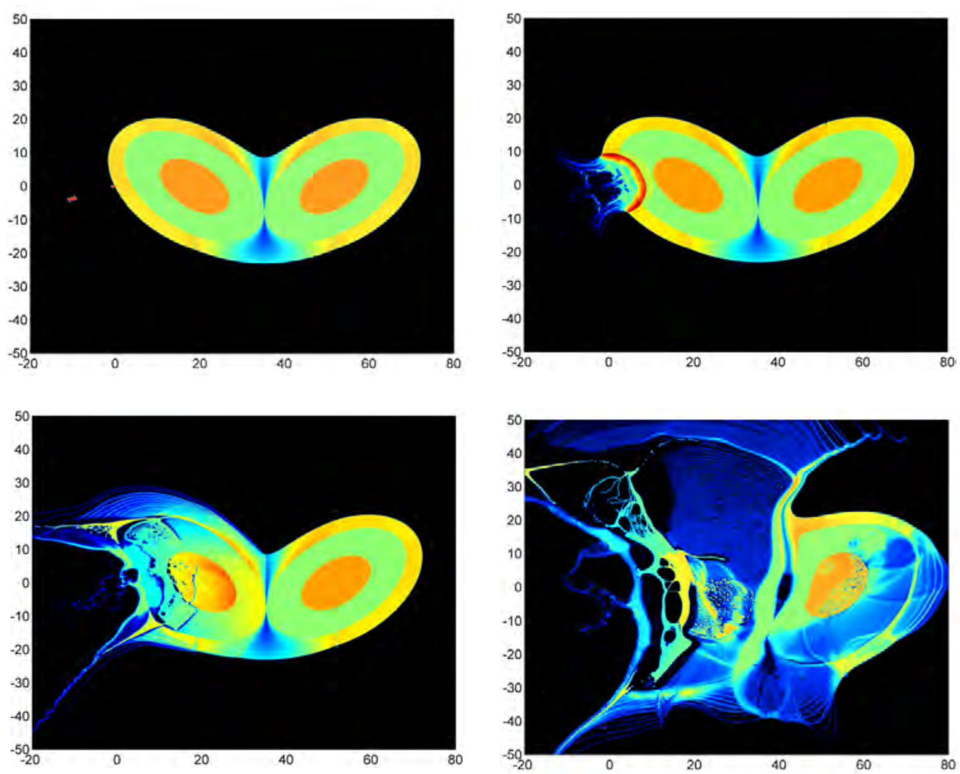

Figure 6: A 70-m asymmetric asteroid model disrupted by a 10-km/s kinetic impact and a subsequent 70-kt nuclear subsurface explosion of the HAIV system [17–19].

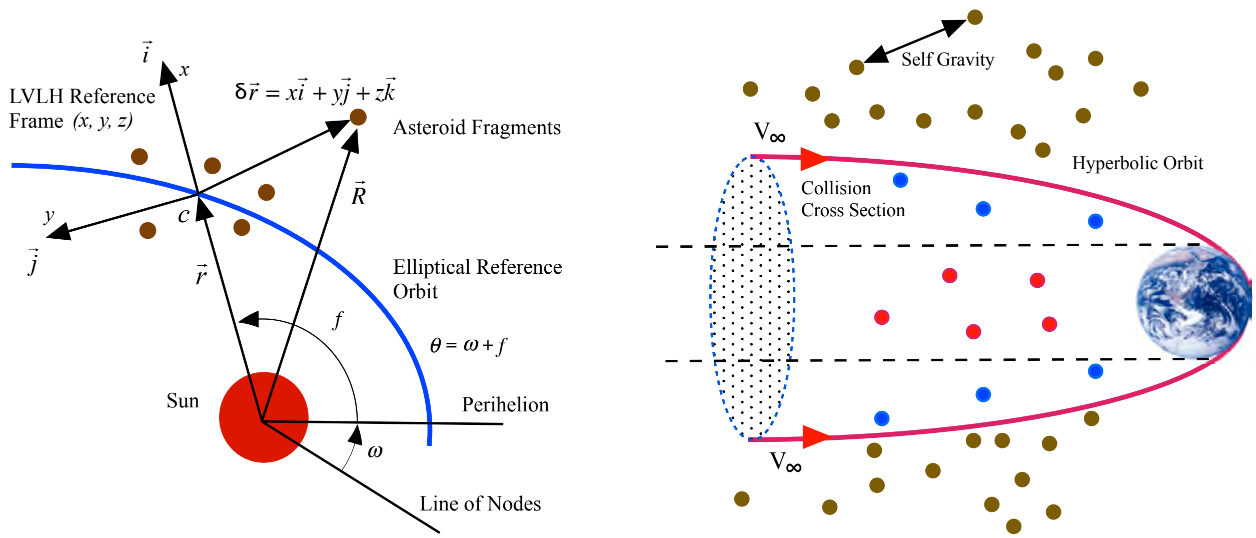

Figure 7: Illustration of the disruption modeling and simulation problem [23].

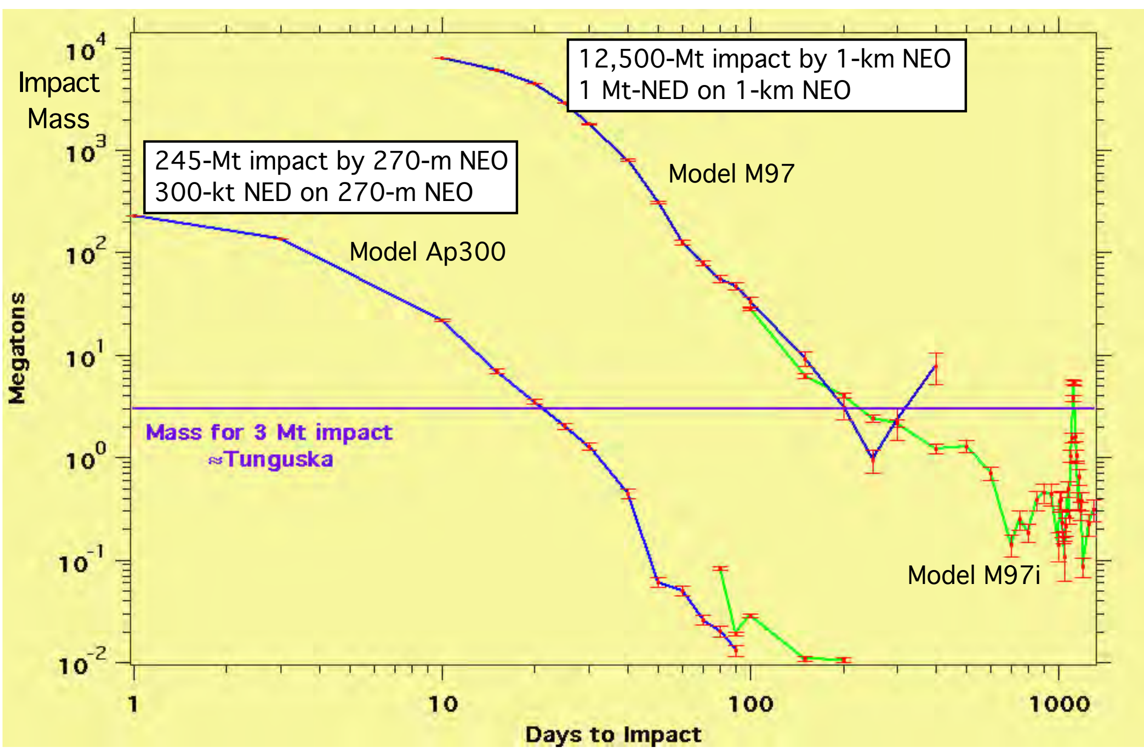

Figure 8: A summary of orbital dispersion simulation study results for nuclear subsurface explosions [23, 24].

an intercept-to-impact time of 200 days if we want to reduce the impact mass to that of the Tunguska event. A 270-m NEO requires an intercept-to-impact time of 20 days for its 300-kt nuclear disruption mission to reduce the impact mass to that of the Tunguska event. Therefore, it can be concluded that under certain conditions, disruption (with large orbital dispersion) is likely to become the only feasible strategy providing considerable impact threat mitigation for some representative, worst-case scenarios. An optimal interception can further reduce the impact mass percentage shown in Fig. 8. However, further study is necessary for assessing the effects of inherent physical modeling uncertainties and mission constraints.

2.2 Planetary Defense Flight Validation (PDFV) Mission Design

A one-week design study was conducted by the MDL (Mission Design Lab) at NASA Goddard Space Flight Center for our NIAC Phase 2 study in 2012 [15]. Its objective was to assess the technical feasibility of deploying a spacecraft to intercept a small (50 to 150 m) NEO within 10 m of its center with 3σ confidence at high relative velocity (>10 km/s) in order to provide a viable planetary defense solution for short warning time scenarios. The MDL performed this assessment by developing a preliminary spacecraft systems concept for the HAIV capable of reliably delivering a notional NED payload to a target NEO and transmitting adequate telemetry for validation of system performance. In addition to the conceptual spacecraft design, the MDL created associated plans for the supporting mission and ground operations in order to provide an overall mission architecture [15].

The MDL worked to design a fully capable HAIV (rather than a simplified test platform) and apply the fully capable design to a suitable practice target NEO. The MDL endeavored to make the flight validation mission affordable through judicious mission design rather than via a scaled-down less expensive flight demonstration platform [15]. The primary design drivers are the high relative velocity at impact and the precision timing required for detonation of the NED in the shallow crater excavated by the leading kinetic impactor portion of the vehicle. The MDL carefully considered what systems equipment should be placed on the lead portion (kinetic impactor) of the HAIV and what should be placed on the follower portion (NED payload carrier). Additionally, high reliability is required because there will only be one opportunity to successfully strike the target NEO. These considerations make it clear that the HAIV will need to be a highly responsive system with onboard autonomous control because of the latency inherent in ground commanding and the highly dynamic environment of the terminal approach phase.

Yet another challenging aspect of this mission is that the size, shape, and rotational state of the NEO will generally not be known in advance of the intercept mission. Design, selection, fuzing, and so on for the NED was purposely placed outside the scope of the MDL study. For the purposes of the study, it was assumed that a dummy mass proxy for the NED payload is installed in the HAIV for the flight validation mission. The NED proxy is modeled as a cylinder 1 m in length with a 0.5 m face diameter and a mass of 300 kg.

The overall configuration/system design of an experimental HAIV flight system is illustrated in Fig. 9. This reference HAIV system consists of the leading impactor portion of the vehicle, the trailing follower portion of the vehicle (carrying the dummy mass proxy for the NED), and the 10-m AstroMast extendable boom that provides the necessary separation between the impactor and follower during NEO impact. This optional configuration employing a deployable boom ensures that the two parts of the vehicle remain collinear during impact. The length of the boom is customized for the particular mission scenario at hand such that the boom length provides an appropriate delay time between when the impactor creates the crater on the NEO and when the follower arrives in the crater and detonates the NED. The appropriate delay time is of course dependent on the terminal approach profile, which is chiefly dominated by the HAIV velocity relative to the NEO at impact.

For launch vehicles, the MDL considered the United Launch Alliance (ULA) Atlas V 400/500 Evolved Expendable Launch Vehicle (EELV) Series, the SpaceX Falcon 9, and the Boeing Delta IV series. All of these launch vehicles provide sufficient mass capability at the desired Earth departure C_3 but the Atlas V is

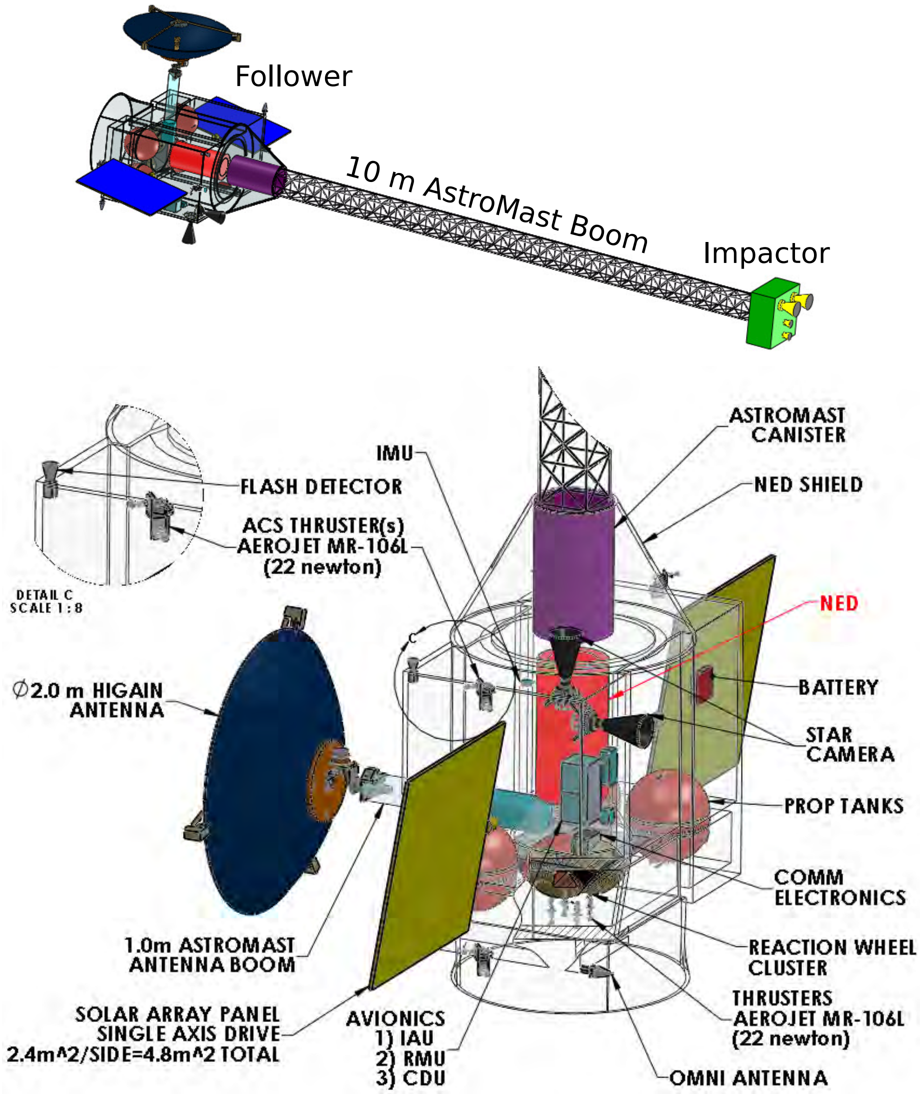

Figure 9: An experimental HAIV flight system designed by the MDL of NASA GSFC [15].

the only EELV currently covered under the NASA Launch Services Program II contract. The HAIV launch configuration in the Atlas V 401 payload fairing is shown in Fig. 10. Accordingly, the notional HAIV flight demo mission assumes launch from Cape Canaveral Air Force Station (CCAFS).

A reference orbital trajectory of a PDFV mission to asteroid 2006 CL9 is shown in Fig. 11, which is similar to the Deep Impact mission trajectory due to the fact that both missions are intended to directly intercept or impact the target object. For the Atlas V 401, the dispersion on the Earth departure C_3 is 0.15 km^2/s^2, which leads to a ΔV for launch dispersion correction of approximately 26 m/s, including maneuver execution errors. The Declination of the Launch Asymptote (DLA) and Right ascension of the Launch Asymptote (RLA) are $-12.0°$ deg and $52.4°$, respectively. The time of injection into the outbound Earth departure hyperbola is 2019-08-02, 08:47:26.443 UTC. The flight time to NEO intercept is 121.41 days, which leads to a time of intercept of 2019-12-01, 18:37:50.443 UTC. The velocity relative to the target at intercept is 11.5 km/s and the approach phase angle is $3°$. The maximum distance from the Earth is 0.36 AU and the maximum distance from the Sun is 1.28 AU. This particular trajectory design was assumed to be the middle of the launch window. The total post-launch ΔV budget for the mission is 37.1 m/s.

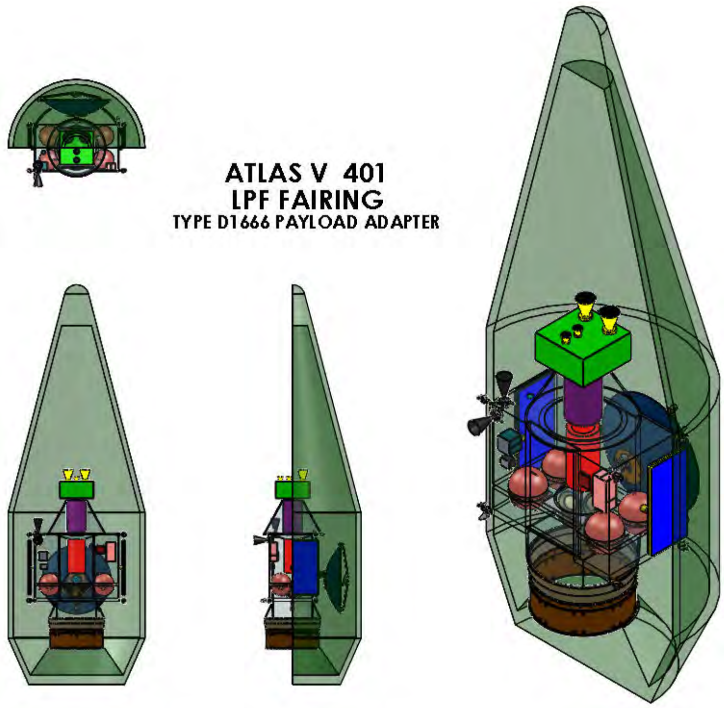

Figure 10: A reference HAIV launch configuration with Atlas V 401 [15].

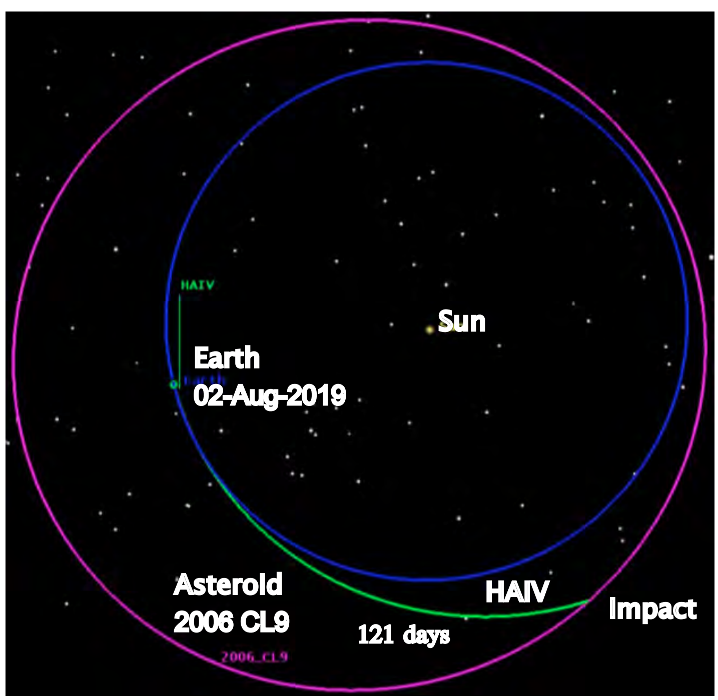

Figure 11: A reference PDFV mission trajectory for a target asteroid (2006 CL9) [15].

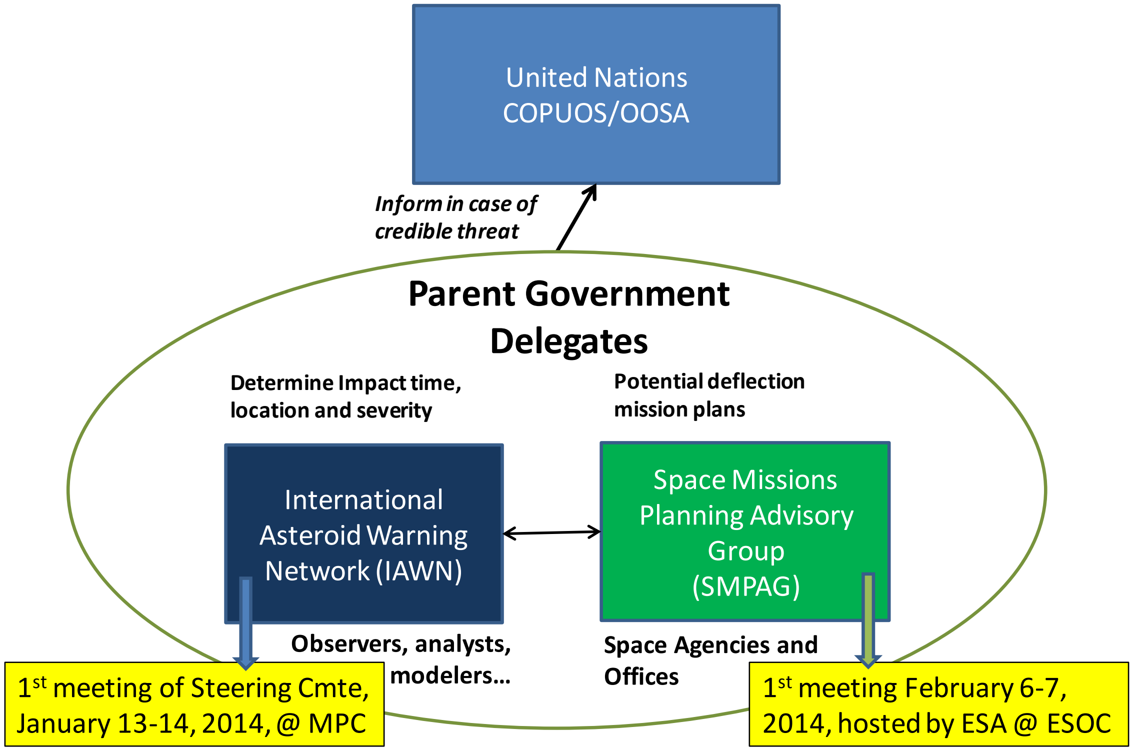

Figure 12: International efforts in preparing for a planetary defense mission. Image courtesy of Lindley Johnson at NASA/NEOO.

The estimated cost of an experimental HAIV flight validation mission is approximately $530M, including the launch vehicle. An approximate cost of $150M is assumed for the notional launch vehicle, which is the Atlas V 401. The cost estimate is comprehensive and includes the complete design, construction, integration, and testing of the spacecraft itself, launch vehicle integration and test, project management, mission operations, ground system, systems integration and test, education and public outreach, and project reserves [15].

3. Recommendations for Planetary Defense

With a mandate from the U.N. Committee on the Peaceful Uses of Outer Space (COPUOS), the Space Mission Planning and Advisory Group (SMPAG) has been established in 2013 to coordinate a global response should a threatening asteroid be found heading toward Earth, as illustrated in Fig. 12. The NEO Observation (NEOO) Program Office of NASA has been coordinating all efforts related to NEO survey, detection, and impact warning.

However, no agency of the U.S. federal government has been officially designated for planning and/or preparing for planetary defense actions prior to detection of a real impact threat (the warning time for which, as noted previously, may be quite short). Therefore, we recommend that a U.S. government agency be formally designated by the Congress for the coordination of all R&D activities of preparing for all planetary defense options, prior to detecting any impact threat.

If we have sufficient warning time (>10 years), then various options, including kinetic impactors, gravity tractors, and nuclear standoff explosions, can be employed for a non-destructive deflection mission. For the more probable impact threat scenario, in which the warning time is less than 5 years, a disruption/dispersion mission employing nuclear explosions is likely to become the only option (other than evacuation of the area

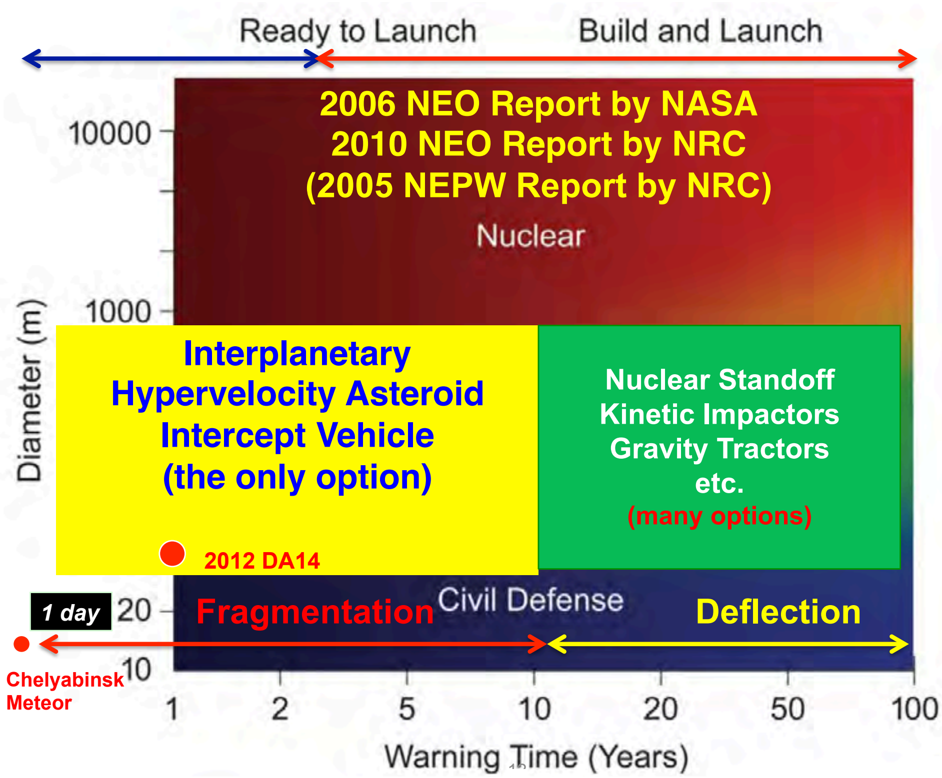

Figure 13: A summary of various mitigation options for planetary defense.

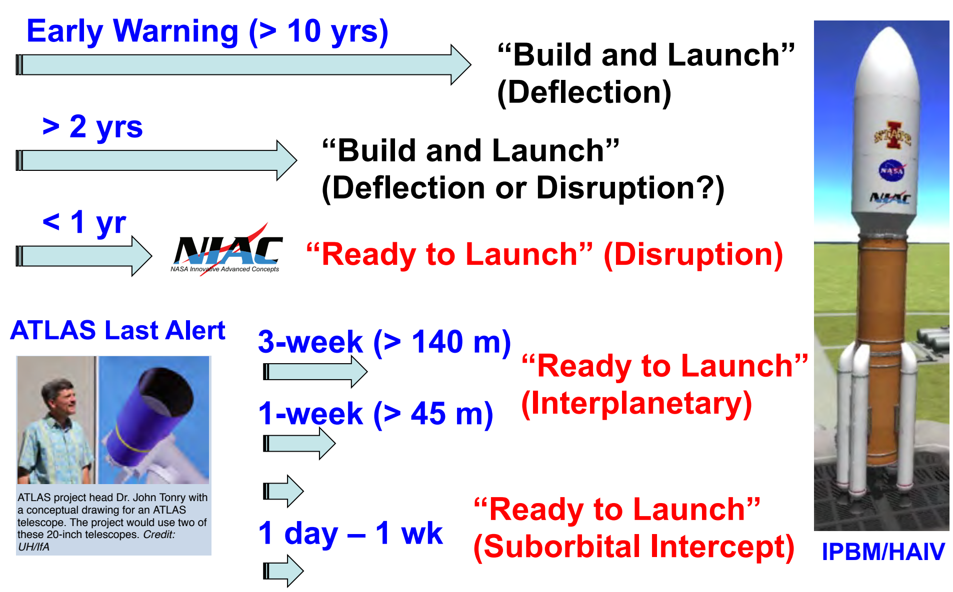

Figure 14: Applicability of the HAIV mission concept to various mission scenarios.

affected by the impact on Earth, assuming the impacting NEO is not large enough to be globally catastrophic). Various mitigation options for a wide range of warning times (1 week to 20 years) are summarized in Figs. 13 and 14.

The mission effectiveness of the proposed HAIV system can be further enhanced by exploiting an asteroid warning system, which is being developed at the University of Hawaii with $5 million funding from NASA. Once this system, called the ATLAS (Asteroid Terrestrial-impact Last Alert System), becomes fully operational in early 2016, it is expected that it will offer a one-week warning for a 45-m asteroid and three weeks for a 140-m asteroid. Provided that such one-week warning from the ATLAS can be assured, a target asteroid >45 m in size can be intercepted and disrupted far outside of Earth's gravitational sphere of influence and, consequently, avoid a potentially troublesome suborbital intercept. It is emphasized that a suborbital intercept may become inevitable for situations with ultra-short warning times of only 1 to 24 hrs as discussed in [25–27].

Most NEO science missions required at least several years, in some cases 5 to 6 years or more, for mission concept development and spacecraft construction prior to launch. It is also important to note that quite a few of these missions originally targeted different asteroids or comets than those that were actually visited. This is because the mission development schedules slipped and launch windows for particular asteroids or comets were missed. Additionally, several of these missions experienced hardware or software failures or glitches that compromised the completion of mission objectives. None of those things would be tolerable for a planetary defense mission aimed at deflecting or disrupting an incoming NEO, especially with relatively little advance warning. Thus, while the successful scientific missions that have been sent to asteroids and comets thus far have certainly provided future planetary defense missions with good heritage on which to build, we are clearly not ready to respond reliably to a threatening NEO scenario.

It is also important to note that most of these missions visited asteroids or comets that range in size from several kilometers to several tens of kilometers. Furthermore, the flyby distances ranged from several tens of kilometers to several thousand kilometers. The sole exception to this is the Deep Impact mission, which succeeded in delivering an impactor to the target in 2007. However, the mission was aided by the fact that comet 9P/Tempel 1 is 7.6 $\times$ 4.9 km in size and, therefore, provided a relatively large target to track and intercept. The Deep Impact mission was not intended to be a PDFV mission. For planetary defense missions requiring NEO intercept, the requirements will be far more stringent: NEO targets with diameters as small as several tens to hundreds of meters will have to be reliably tracked and intercepted at hypervelocity speeds, with impact occurring within mere meters of the targeted point on the NEO's surface. This will require significant evolution of the autonomous guidance and control technology currently available for science missions to NEOs.

Furthermore, none of the potential planetary defense mission payloads (e.g., kinetic impactors, nuclear explosives) to deflect or disrupt NEOs have ever been tested on NEOs in the space environment. Significant work is, therefore, required to appropriately characterize the capabilities of those payloads, particularly the ways in which they physically couple with NEOs to transfer energy or alter momentum, and ensure robust operations during an actual emergency scenario.

With regard to the need for planetary defense spacecraft system testing, it is important to note that there is currently no solicitation for planetary defense flight validation mission proposals. Such missions are necessarily similar in cost to science missions (e.g., Discovery or New Frontiers), yet there is no established mechanism for funding planetary defense flight validation missions. So, there is a need for planetary defense flight validation mission funding. It is worth pointing out that such missions will naturally, by their intrinsic nature, return significant amounts of science data even though they are not primarily science missions.

Finally, the very nature of the HAIV design (and the motivation for its design) underscores the need for a dedicated space-based NEO survey telescope located far from Earth's vicinity. Such a telescope would be an affordable and cross-cutting system that simultaneously serves the planetary defense, science, and exploration communities. Completing the NEO population survey as soon as possible is the best way to maximize the amount of warning time available to us should we find a NEO on an Earth-impacting trajectory.

That cannot be done using Earth-based telescopes, and such telescopes will always be blind to the sunward direction (from which the Chelyabinsk impactor approached); a space-based NEO survey will not have the same blind spot. Although we are designing the HAIV to address short warning time situations because they are the most stressing cases and there will always be a risk of such a case occurring, we want to emphasize that doing our best to avoid short warning time scenarios by deploying a space-based NEO survey telescope is the most prudent course of action. Unfortunately, as with planetary defense flight validation missions, the NEO survey telescope cannot seem to find a funding source within NASA. Therefore, we recommend that NASA make the funding of a dedicated space-based NEO survey telescope a top priority, followed by funding for planetary defense flight validation missions.

4. Concluding Remarks

In summary, it is time to initiate a planetary defense flight validation program, mandated by the Congress, for demonstrating, validating, and refining planetary defense technologies in space, so that we will be properly prepared to respond effectively when a near-Earth object (NEO) on a collision course with Earth is discovered. It will require at least 5 years of further development and space flight validation testing before operational planetary defense technologies could be employed in a real short warning time situation. Now is the time to initiate such preparations. Waiting until a threatening NEO is discovered will be far, far too late. In addition, it is time to build and launch a dedicated space-based NEO survey telescope stationed far from Earth's vicinity. Such a system will be a key asset that simultaneously benefits planetary defense, fundamental solar system science, and space exploration.

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